Experimental and numerical study on the shear-layer instability in a 5:1 benchmark rectangular cylinder

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Experimental and numerical study on the shear-layer instability in a 5:1 benchmark rectangular cylinder

C. Mannini*, A. Mariotti, M.V. Salvetti

*claudio.mannini@unifi.it

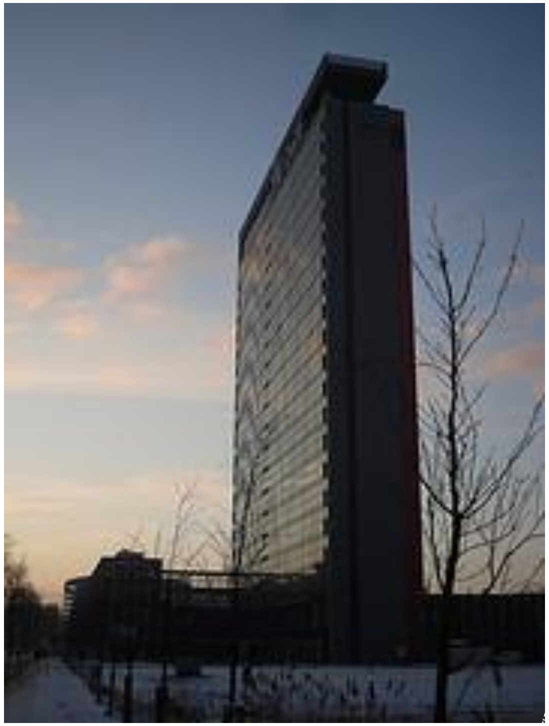
Summary

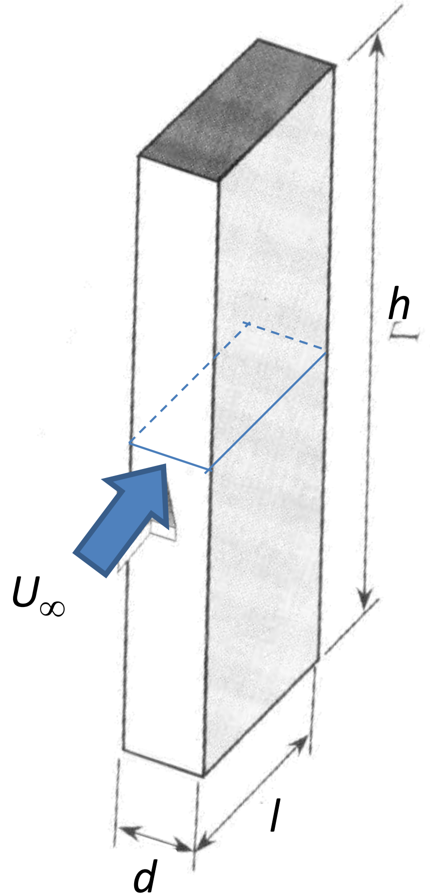
1. Benchmark BARC: open issues
2. Numerical LES study
3. Experimental study
4. Comparison of results
5. Focus on shear-layer dynamics
6. Conclusions (provisional)

Benchmark on the Aerodynamics of a Rectangular 5:1 Cylinder

The rectangular 5:1 cylinder as an archetypal geometry for tall buildings, towers and bridges.

Despite its relatively simple geometry, it contains most of the difficulties found in realistic bluff bodies.

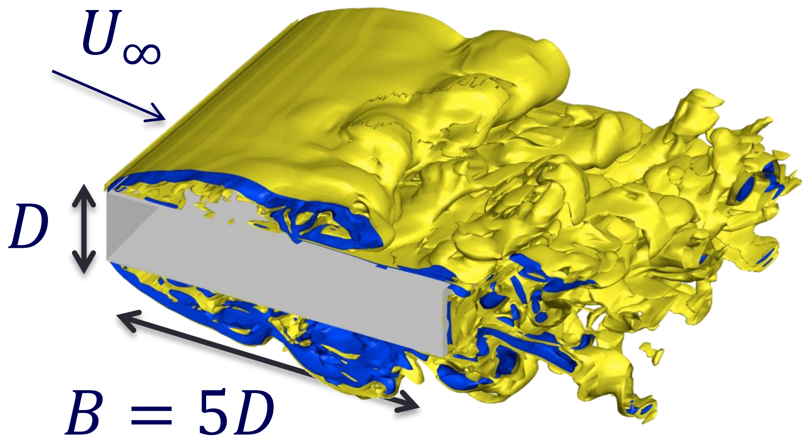




In spite of the simple geometry, the flow is complex.

Turbulent wake with separation from the upstream corners and intermittent reattachment on the cylinder sides.

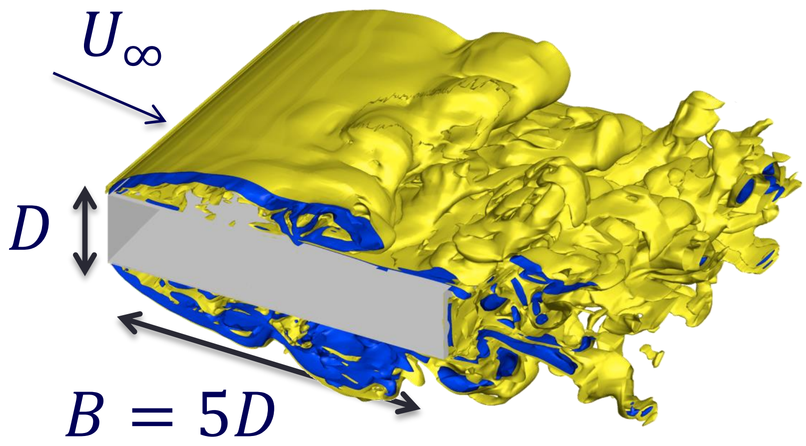
Mechanism of vortex shedding dominated by the impinging shear-layer instability.



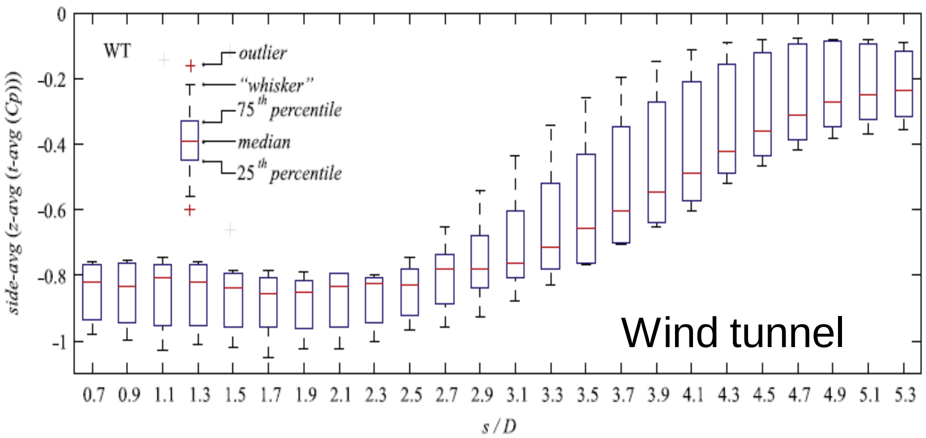
$$Re = \frac{U_\infty D}{\nu} = 2\times10^4 \text{ to } 6\times10^4$$

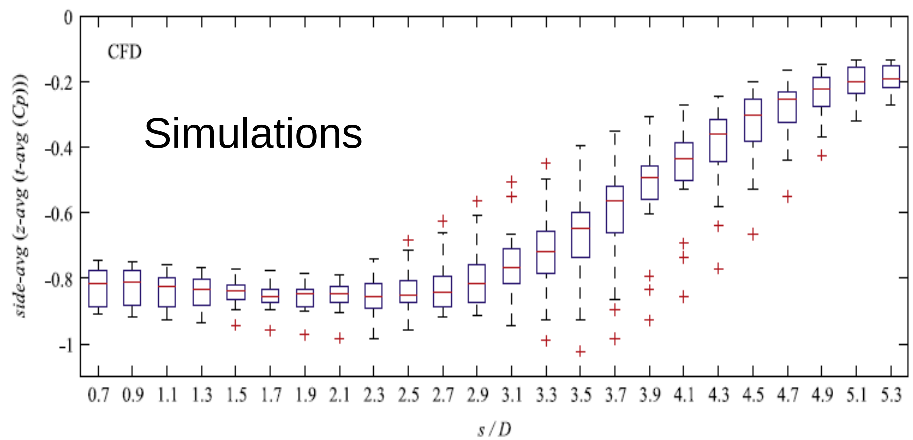
Benchmark on the Aerodynamics of a Rectangular 5:1 Cylinder

- ✓ Over 70 numerical and experimental realizations of the BARC flow configuration have been collected; 51% of the numerical contributions were LES.
- ✓ Significant dispersion of some flow quantities of interest, such as the mean pressure distribution on the cylinder side.



Mean pressure coefficient





Bruno, L., Salvetti, M. V., Ricciardelli, G. (2014): Benchmark on the Aerodynamics of a Rectangular 5:1 Cylinder: An overview after the first four years of activity, *Journal of Wind Engineering and Industrial Aerodynamics* 126, 87-106

PREVIOUS RESULTS

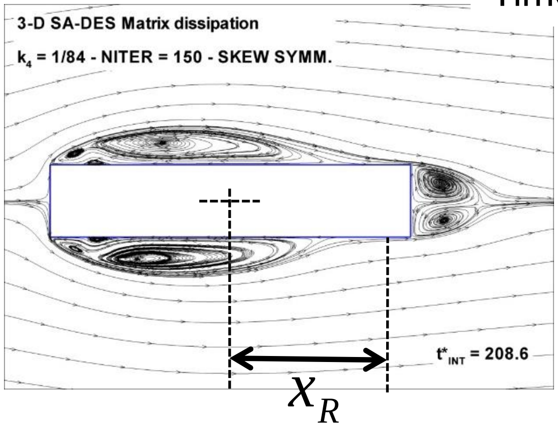
Mannini, C., Soda, A., Schewe, G. (2011): Numerical investigation on the three-dimensional unsteady flow past a 5:1 rectangular cylinder, *Journal of Wind Engineering and Industrial Aerodynamics* 99 (4), 469-482

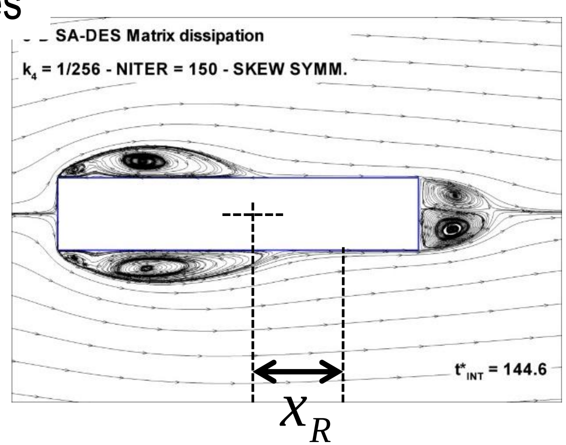
- **Finite-volume compressible code**
- **SA-DES simulation**

Fine spanwise resolution of the grid:

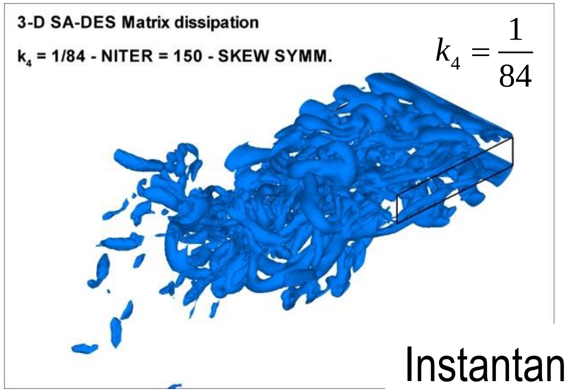
$$\Delta z/D = 0.078$$

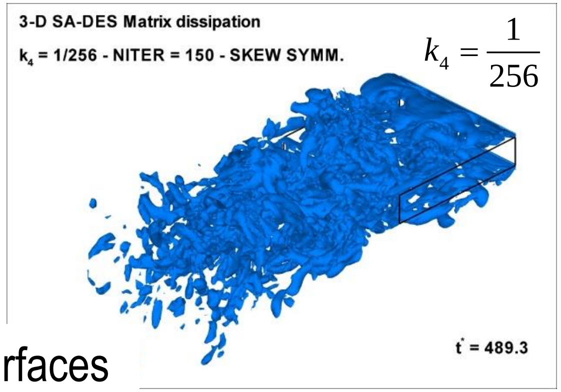
Time-averaged streamlines





Reducing artificial viscosity



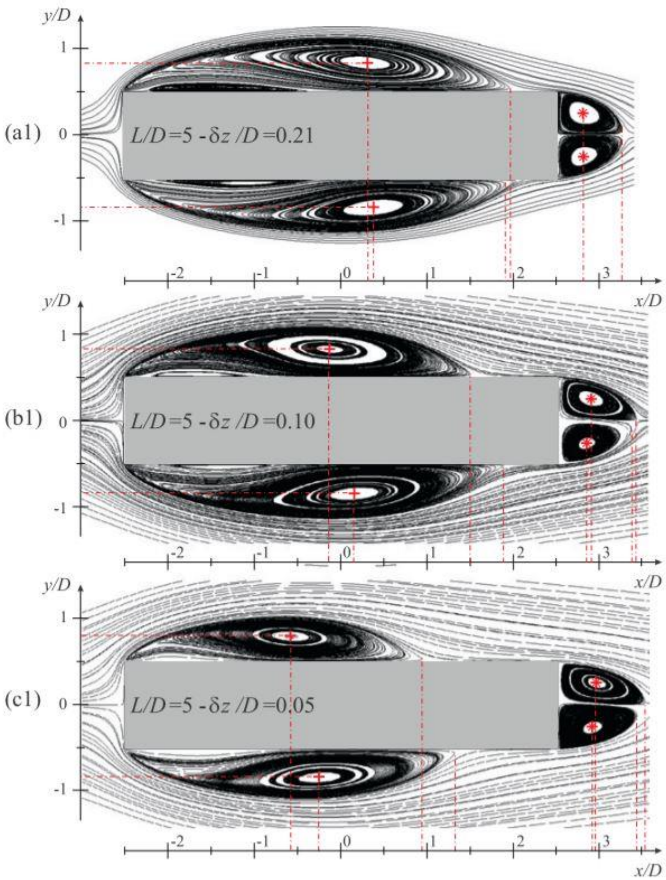


Instantaneous *Q*-invariant isosurfaces

PREVIOUS RESULTS

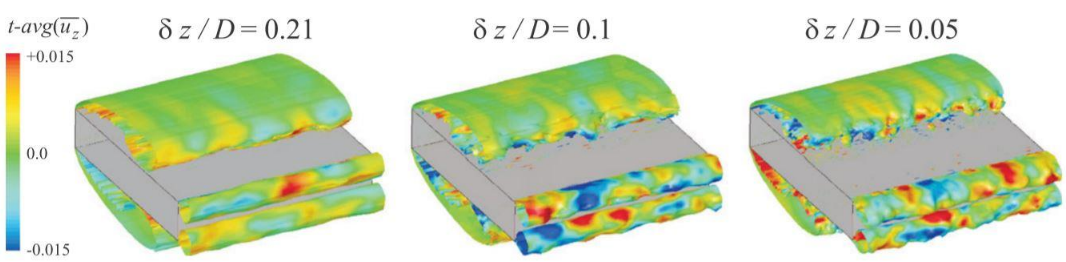
Bruno, L., Coste, N., Fransos, D. (2012): Simulated flow around a rectangular 5:1 cylinder: Spanwise discretization effects and emerging flow features, *Journal of Wind Engineering and Industrial Aerodynamics* 104-106, 203-215

Time-averaged streamlines



- **Finite-volume incompressible code**
- **LES simulation**
- **Transport kinetic energy model for SGS dissipation**

Increasing the spanwise resolution of the grid



Time-averaged *Q*-invariant isosurfaces

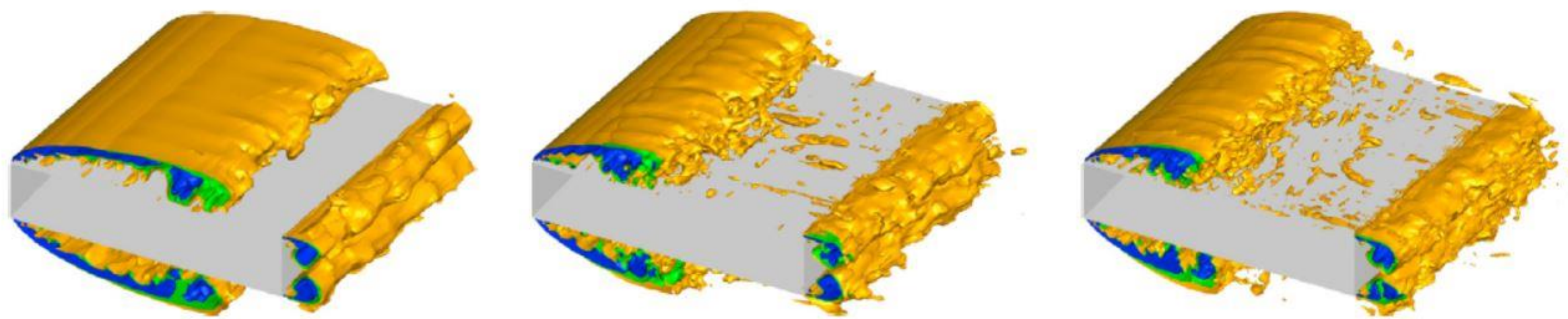
PREVIOUS RESULTS

Mariotti, A., Siconolfi, L., Salvetti, M. V. (2017): Stochastic sensitivity analysis of large-eddy simulation predictions of the flow around a 5:1 rectangular cylinder, *European Journal of Mechanics B/Fluids* 62, 149-165

- **Spectral element incompressible code**
- **LES simulation**

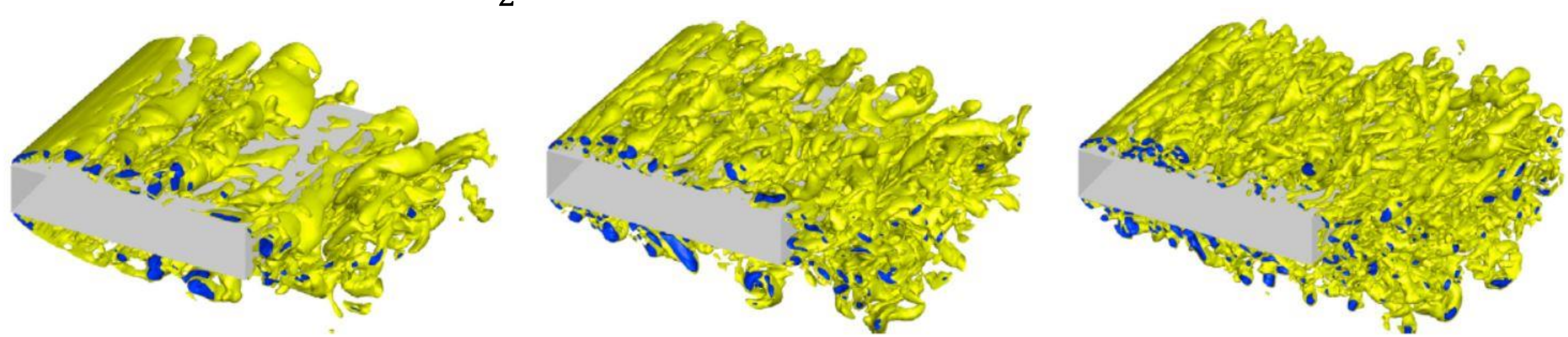
Increasing the spanwise resolution of the grid and/or reducing the SGS-like dissipation

Time-averaged vortex indicator λ_2 isosurfaces



(a) $(w_2, \Delta z_1)$. (b) $(w_2, \Delta z_2)$. (c) $(w_2, \Delta z_4)$.

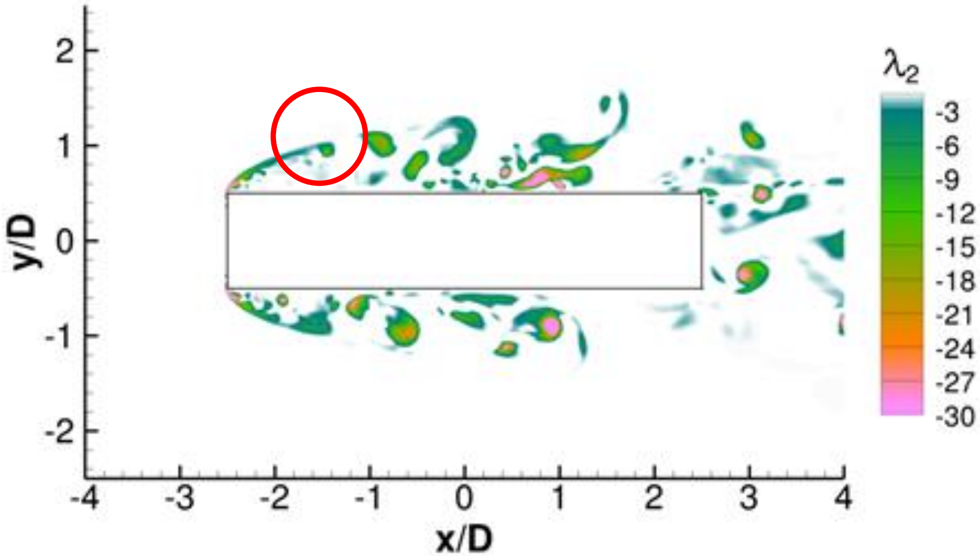
Instantaneous vortex indicator λ_2 isosurfaces



(g) $(w_2, \Delta z_1)$. (h) $(w_2, \Delta z_2)$. (i) $(w_2, \Delta z_4)$.

SCOPE OF THE WORK

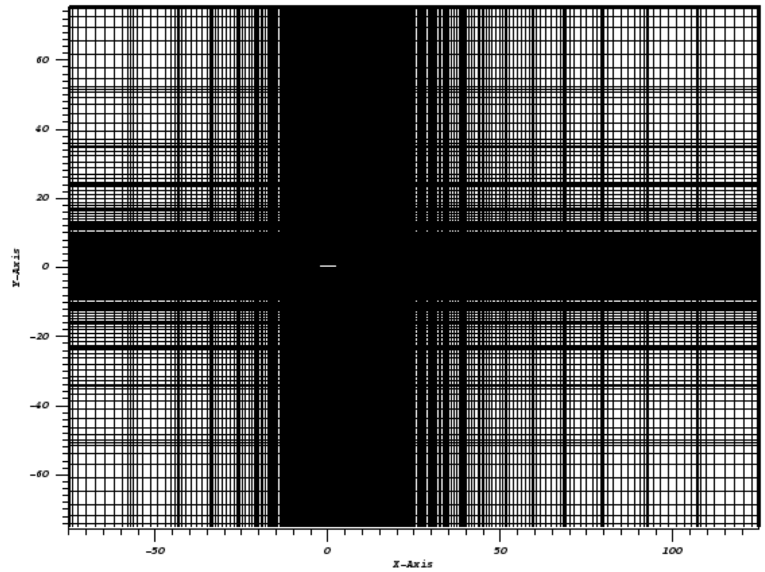
- In **very different LES studies**, we observed a significant reduction in the length of the mean recirculation bubbles (in disagreement with experimental results) while **refining the mesh in the spanwise direction** and/or **reducing SGS or artificial dissipation**.
- Experimental and numerical LES investigations were further pursued to understand the reason for this particular behavior of the LES results.
- Special focus to the dynamics of the separated shear layers and their instability.



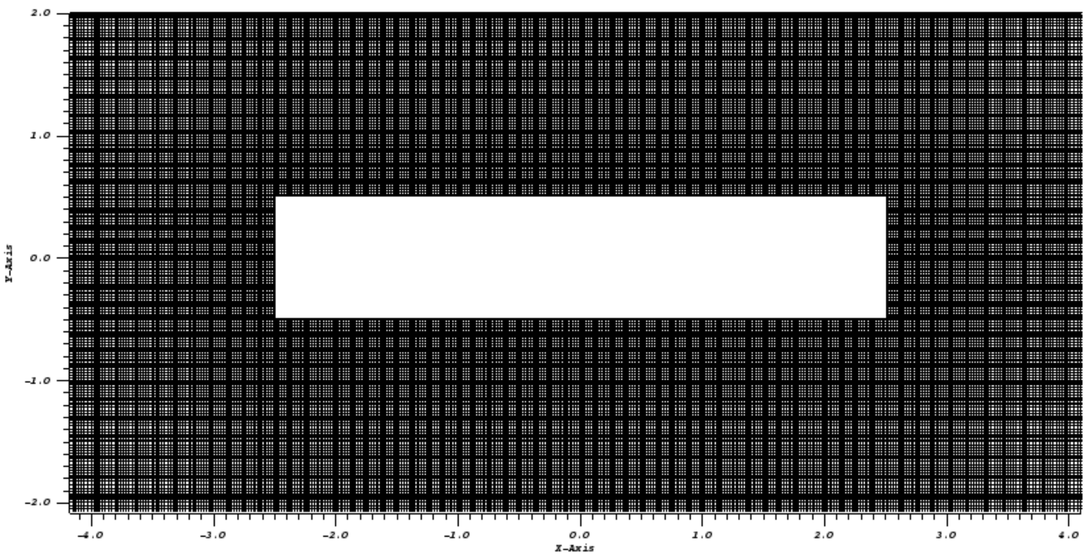
NUMERICAL SETUP

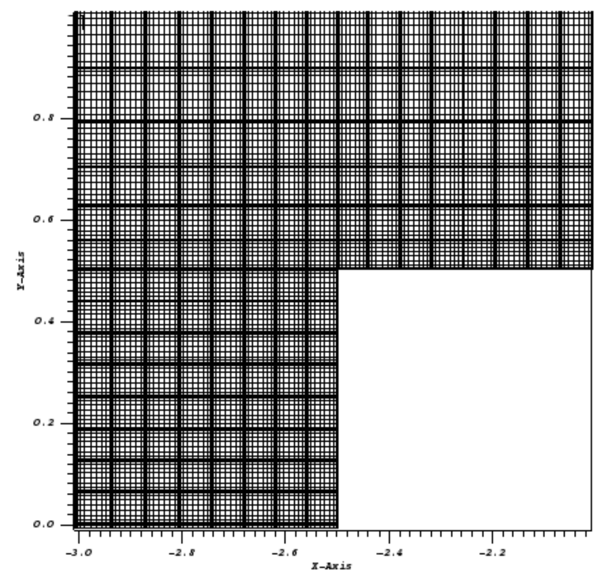
LES were carried out using NEK5000 (open-source spectral element code):

- ☞ N-th order Lagrangian polynomial interpolants in each grid element (N-2 for pressure).
  N = 6 in the present simulations
- ☞ Third-order backward finite difference scheme for time advancing.



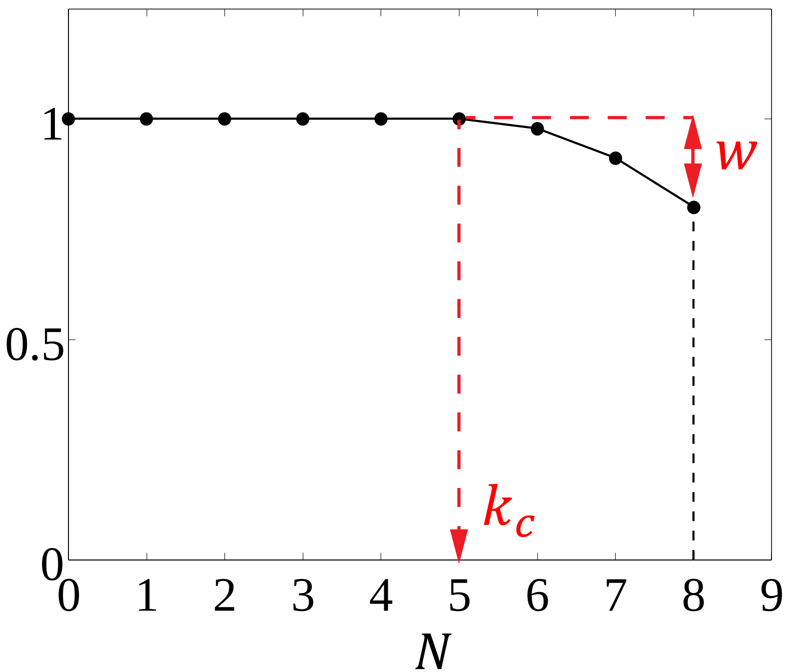
Rectangular spectral element size:
$\Delta x = \Delta y = 0.125D$





NUMERICAL SETUP

✓ LES based on explicit modal filtering.
Sharp cut-off for the modes up to k_c (unfiltered), and quadratic transfer function for the modes $k_c < p \leq N$, which can be tuned through a weighting parameter, w.
This modal filter provides a dissipation in the highest resolved modes, which can be interpreted as a SGS dissipation (*e.g.* Mathew *et al.*, 2003, Domaradzki, 2010).

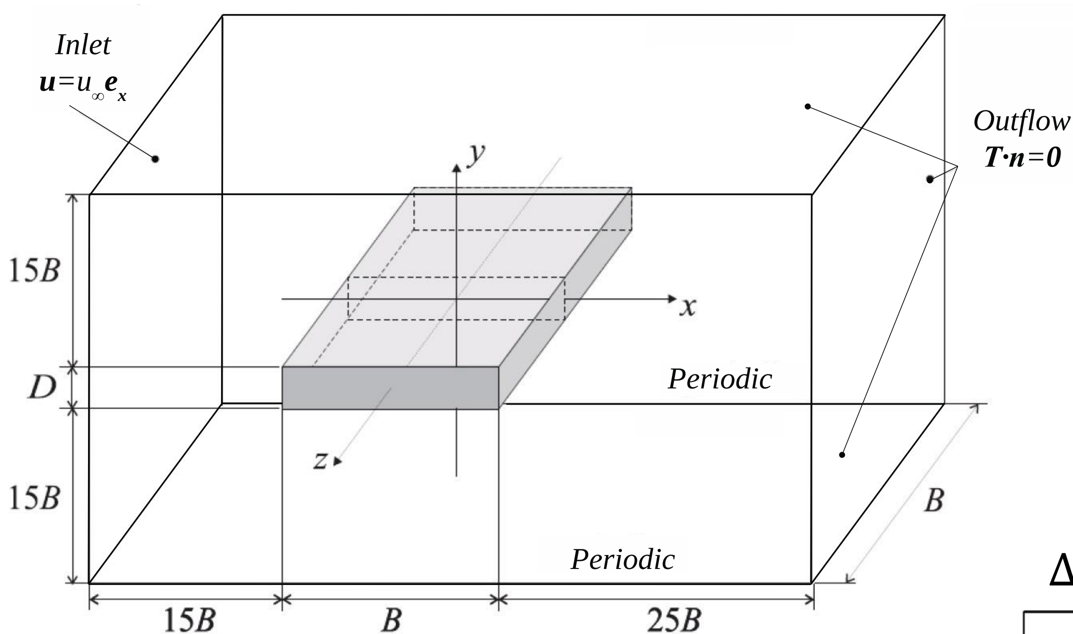


Transfer function of the explicit modal filter:

$$\begin{cases} \sigma_k = 1 & k \leq k_c \\ \sigma_k = 1 - w\left(\dfrac{k - k_c}{N - k_c}\right)^2 & k_c < k \leq N \end{cases}$$

Mariotti, A., Siconolfi, L., Salvetti, M. V. (2017): Stochastic sensitivity analysis of large-eddy simulation predictions of the flow around a 5:1 rectangular cylinder, *European Journal of Mechanics B/Fluids* 62, 149-165

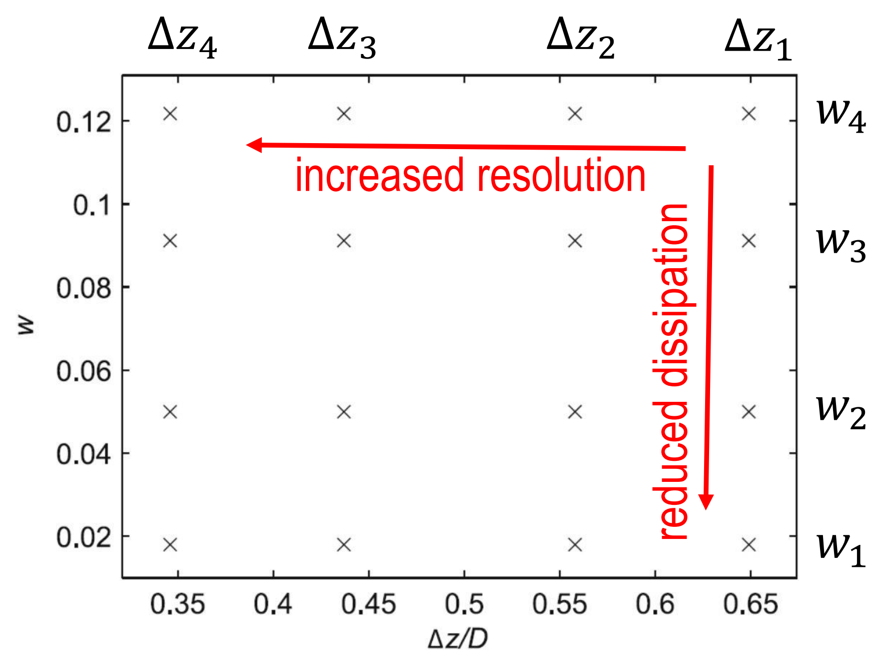
NUMERICAL SETUP



16 LES simulations

$\Delta z \in [0.346D, 0.649D]$

$w \in [0.018, 0.122]$

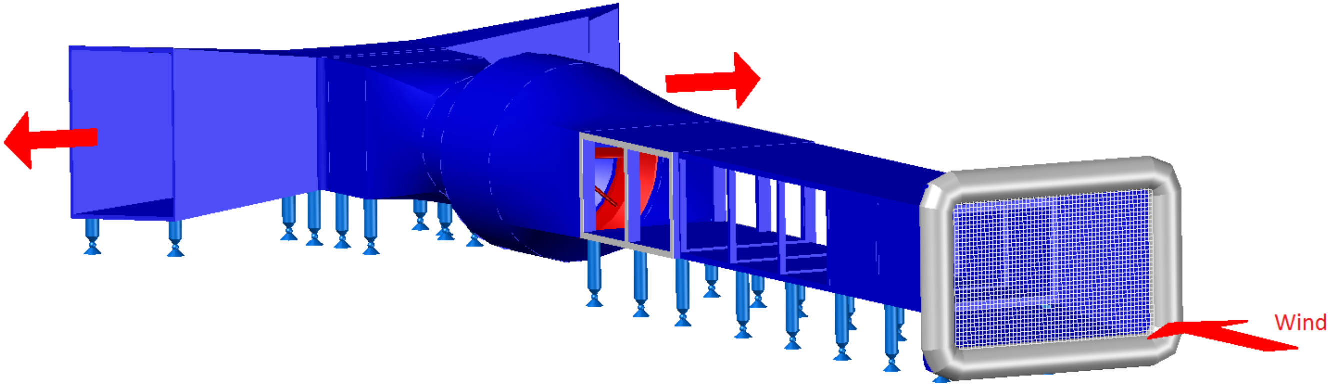


- ✓ Polynomial order: N = 6
- ✓ Filtered modes: $N - k_c = 3$
- ✓ Re_D = 40,000
- ✓ No free-stream turbulence
- ✓ Δt = 0.004 (CFL ≈ 0.37)

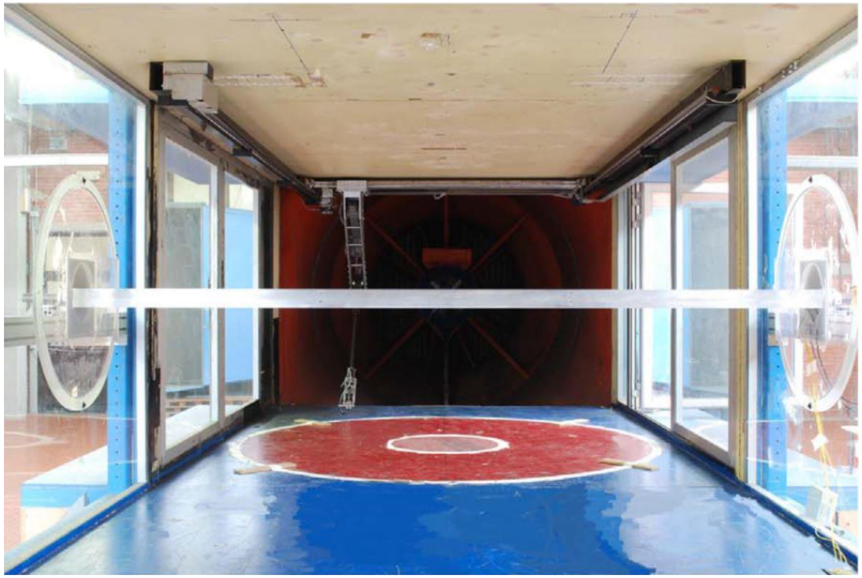
EXPERIMENTAL STUDY

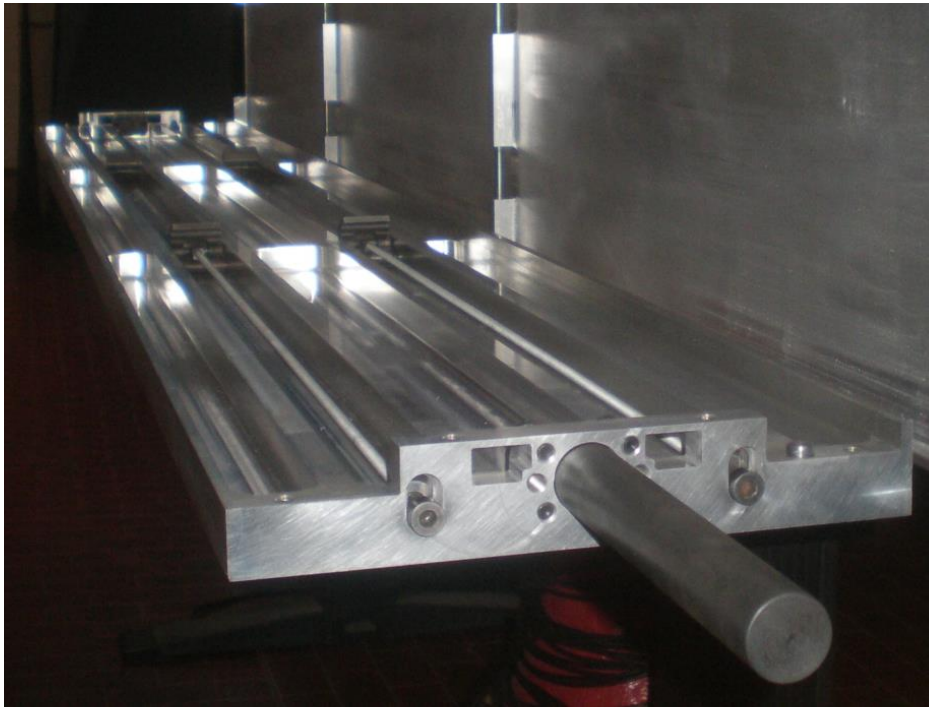
Tests were performed in the CRIACIV Boundary Layer Wind Tunnel (Prato, Italy)

- ✓ Test section 2.42 m × 1.60 m
- ✓ Total length: 22 m
- ✓ Flow speed up to 30 m/s
- ✓ Free-stream turbulence intensity: ~ 0.7%

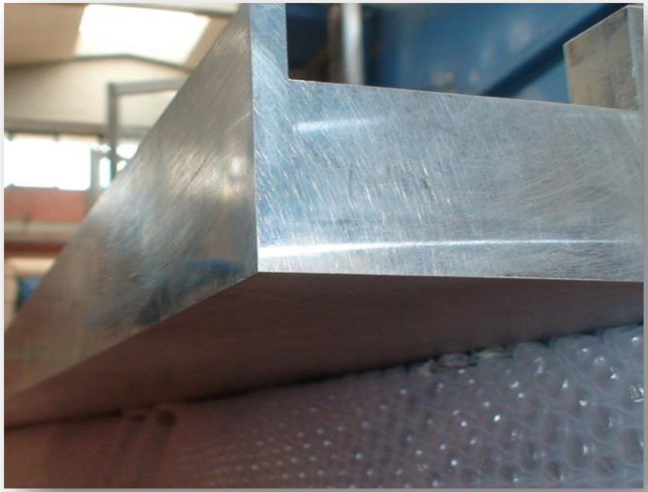


EXPERIMENTAL STUDY



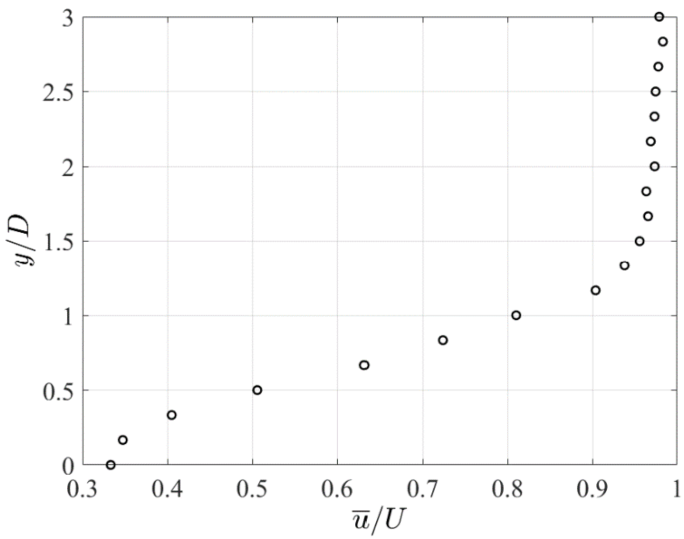


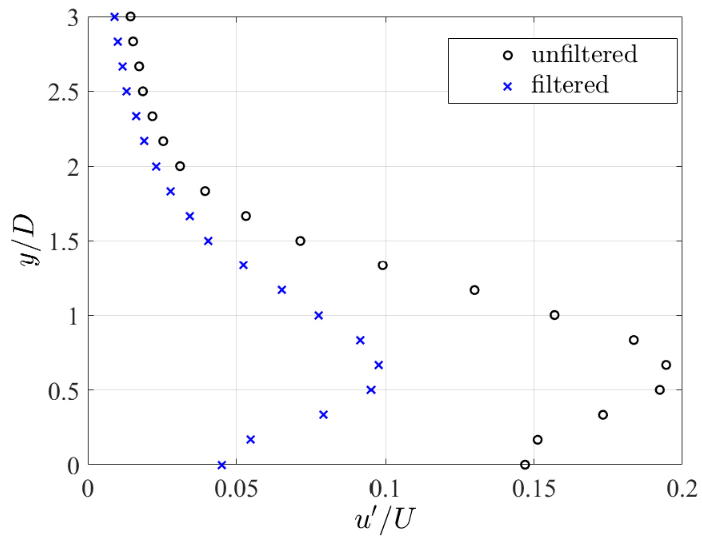
- ✓ B = 300 mm
- ✓ D = 60 mm
- ✓ L = 2380 mm
- ✓ L/B = 7.93
- ✓ Made of a special aluminum alloy
- ✓ 3.75% blockage ratio (for $\alpha = 0°$)



EXPERIMENTAL STUDY

- ✓ Measurements of pressures, forces and flow velocity fluctuations
- ✓ Effect of the Reynolds number
- ✓ Effect of the angle of attack
- ✓ Effect of free-stream turbulence intensity and integral length scale
- ✓ For the first time in the benchmark, wake measurements were carried out

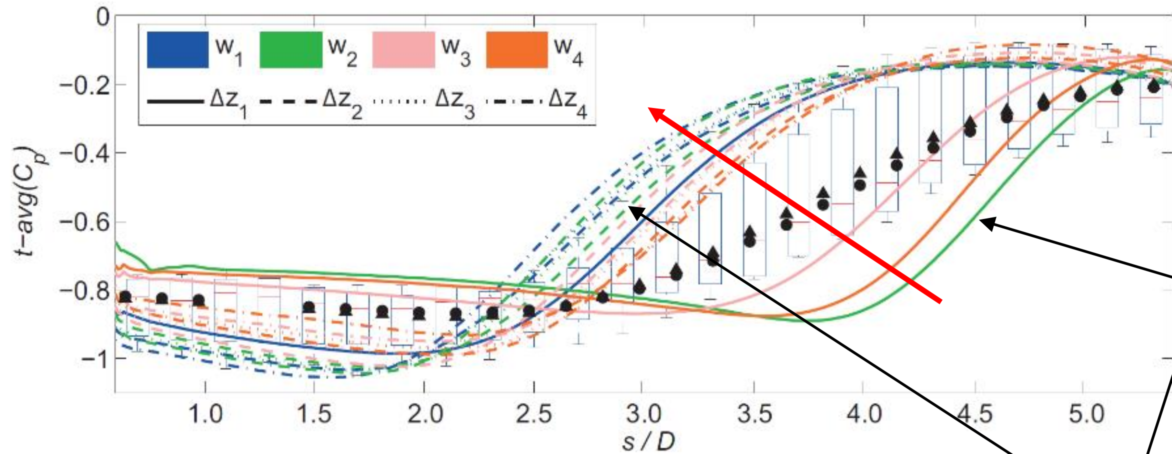




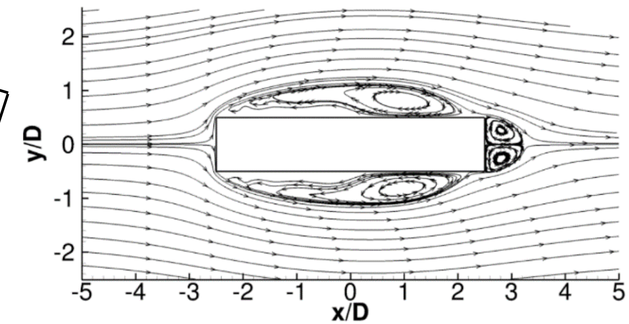
Mannini, C., Marra, A. M., Pigolotti, L., Bartoli, G. (2017):The effects of free-stream turbulence and angle of attack on the aerodynamics of a cylinder with rectangular 5:1 cross section, *Journal of Wind Engineering and Industrial Aerodynamics* 161, 42-58

NUMERICAL vs. EXPERIMENTAL RESULTS

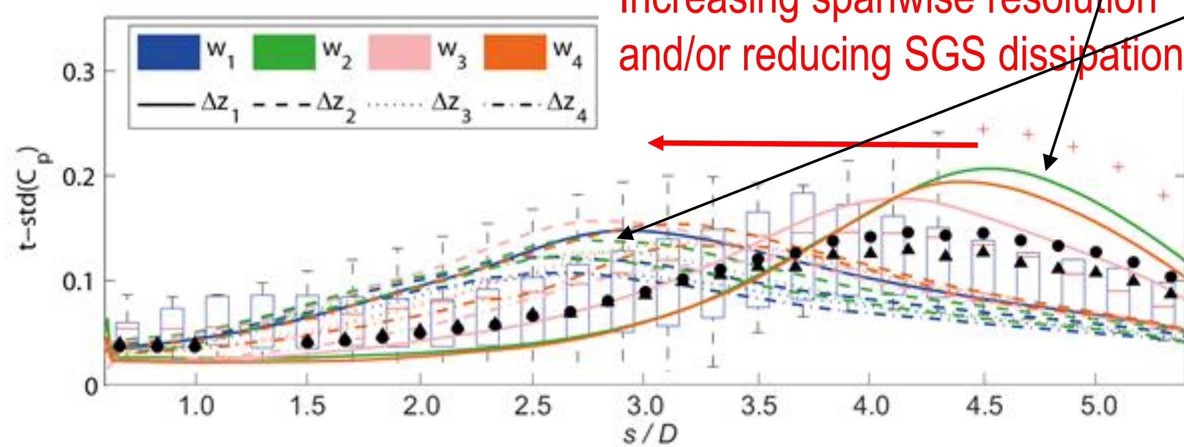
- ● Exp. – $Re = 56{,}700$
- ▲ Exp. – $Re = 112{,}200$

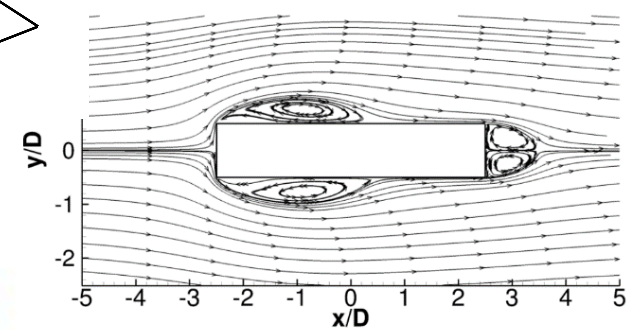


$\Delta z_1\ , w_2$



Increasing spanwise resolution
and/or reducing SGS dissipation

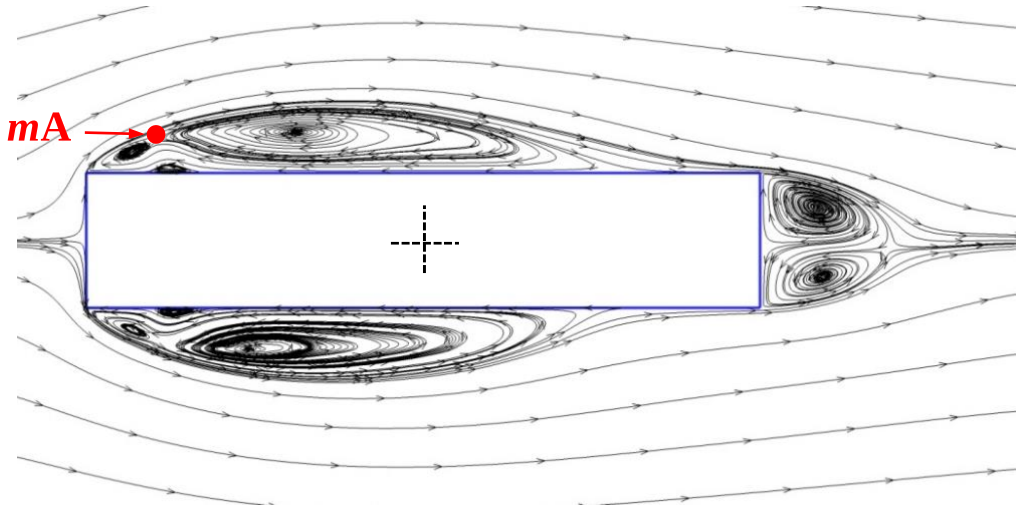




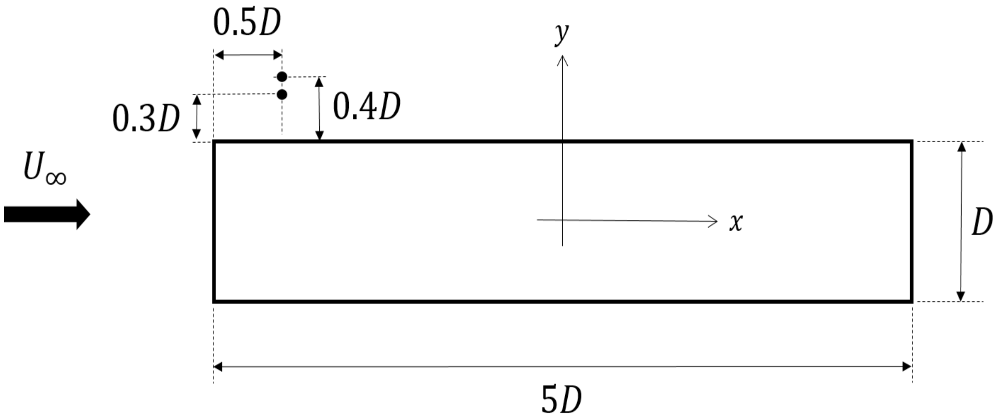
$\Delta z_2\ , w_2$

FOCUSING ON THE SHEAR-LAYER DYNAMICS

Mannini *et al*., JWEIA 2011

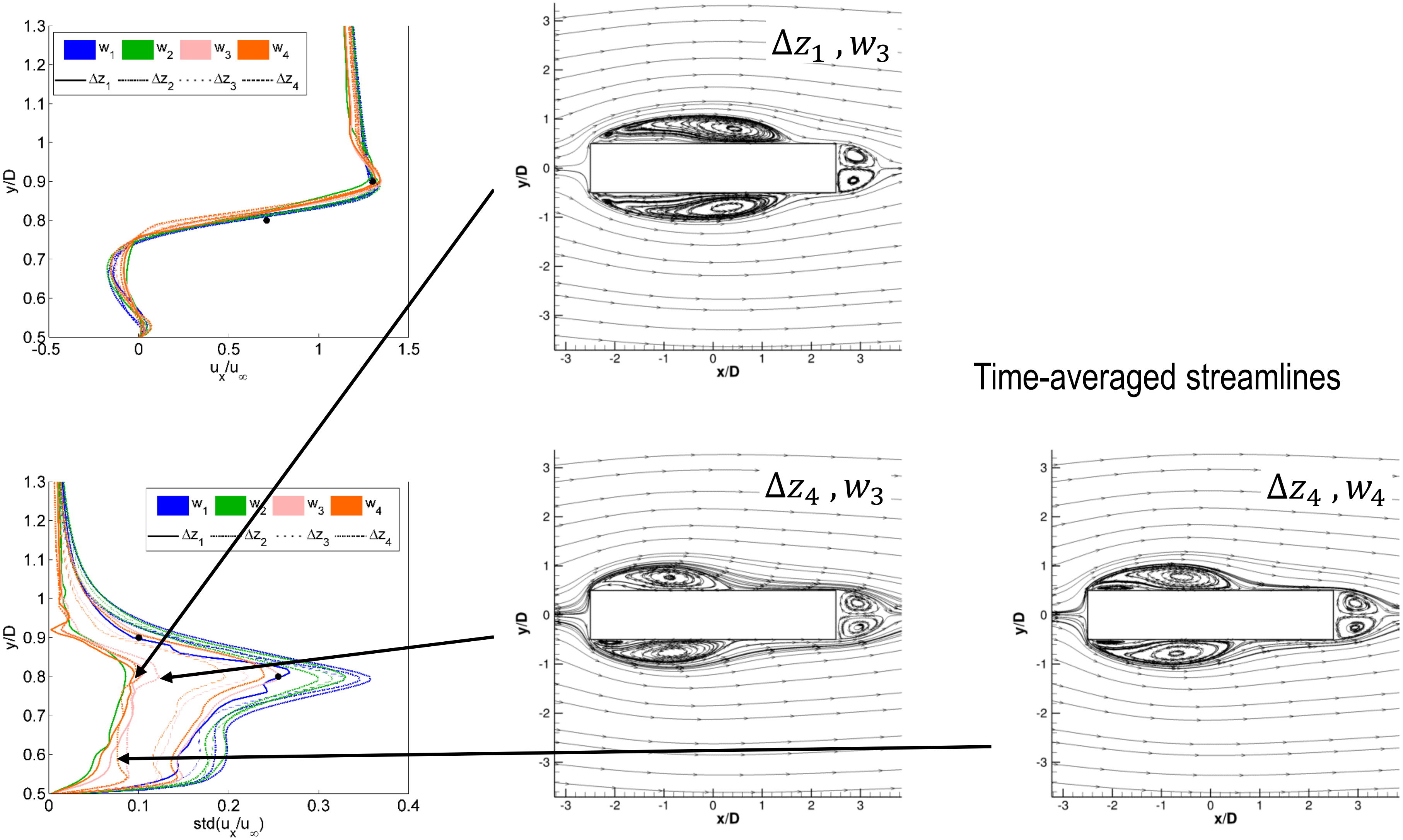


- ✓ Single-component hot-wire anemometer
- ✓ Sampling rate: 2000 Hz
- ✓ Smooth flow and $\alpha = 0°$



FOCUSING ON THE SHEAR-LAYER DYNAMICS

Streamwise mean velocity component

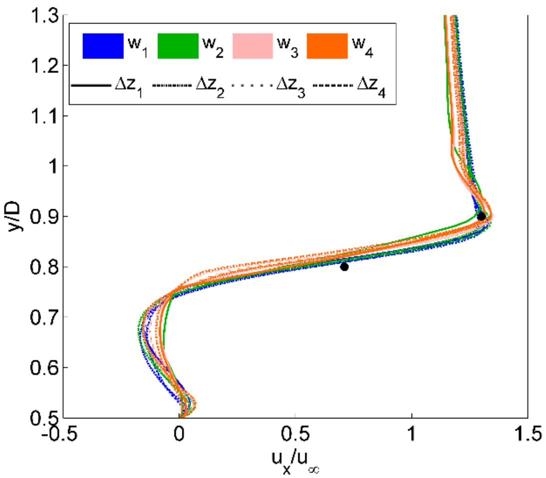


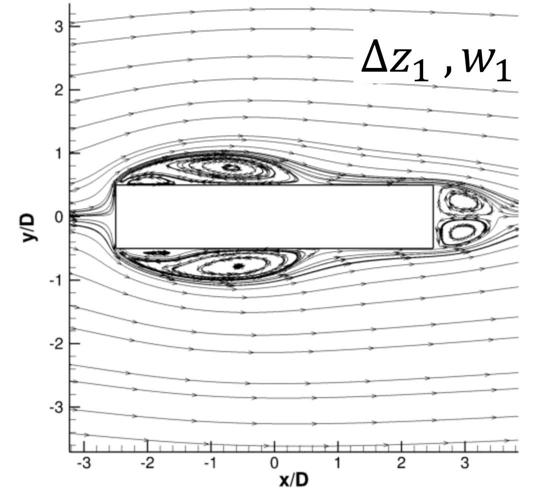
Time-averaged streamlines

RMS of the streamwise velocity component

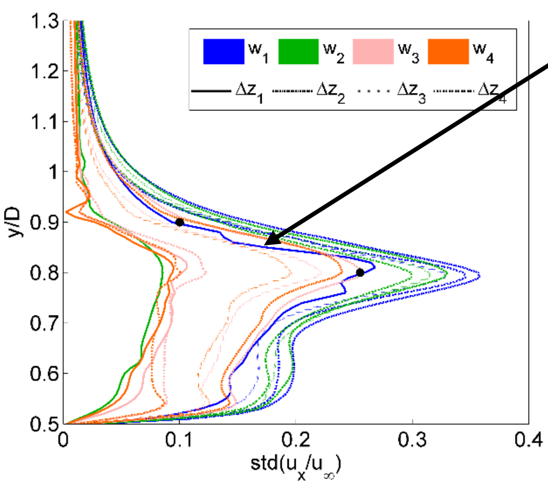
FOCUSING ON THE SHEAR-LAYER DYNAMICS

Streamwise mean velocity component





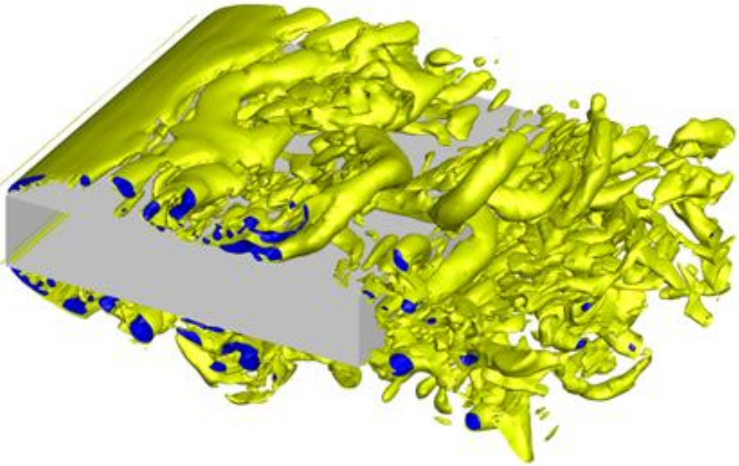
Time-averaged streamlines



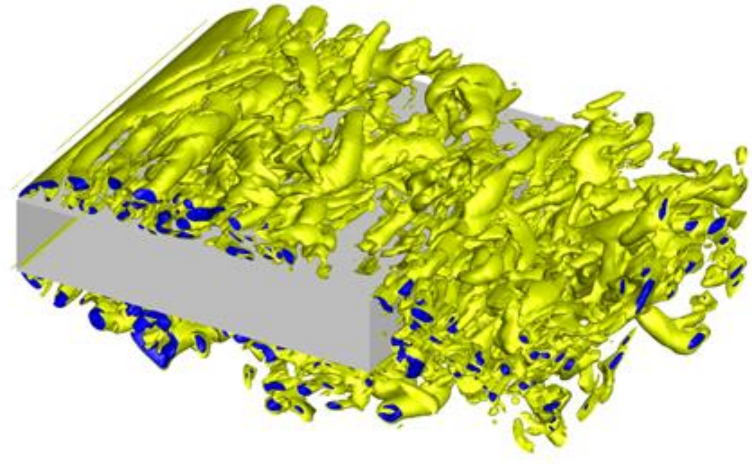
- ✓ First and second-order statistics of velocity fluctuations at this shear-layer location do not exhibit strong correlation with the length of the recirculation bubbles.

RMS of the streamwise velocity component

FOCUSING ON THE SHEAR-LAYER INSTABILITY



$\Delta z_1, w_2$

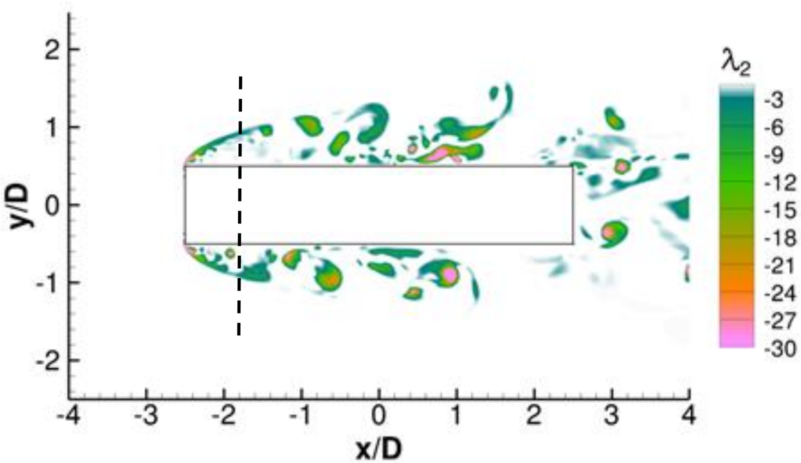


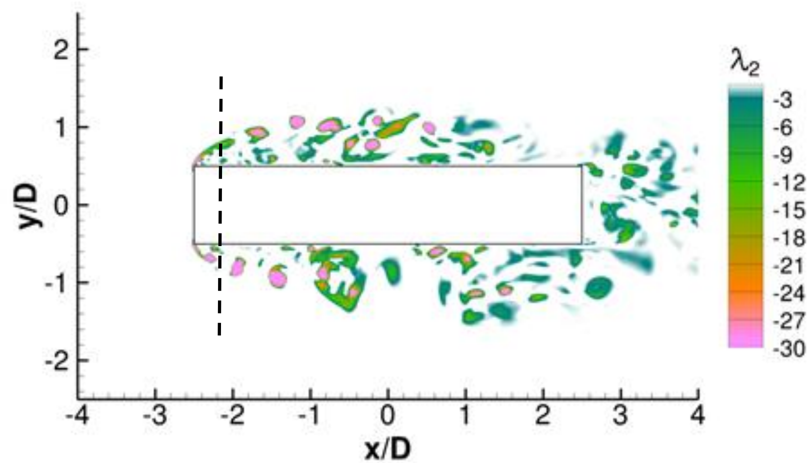
$\Delta z_2, w_2$

$$\frac{f_{KH} D}{U_\infty} \approx 0.7$$

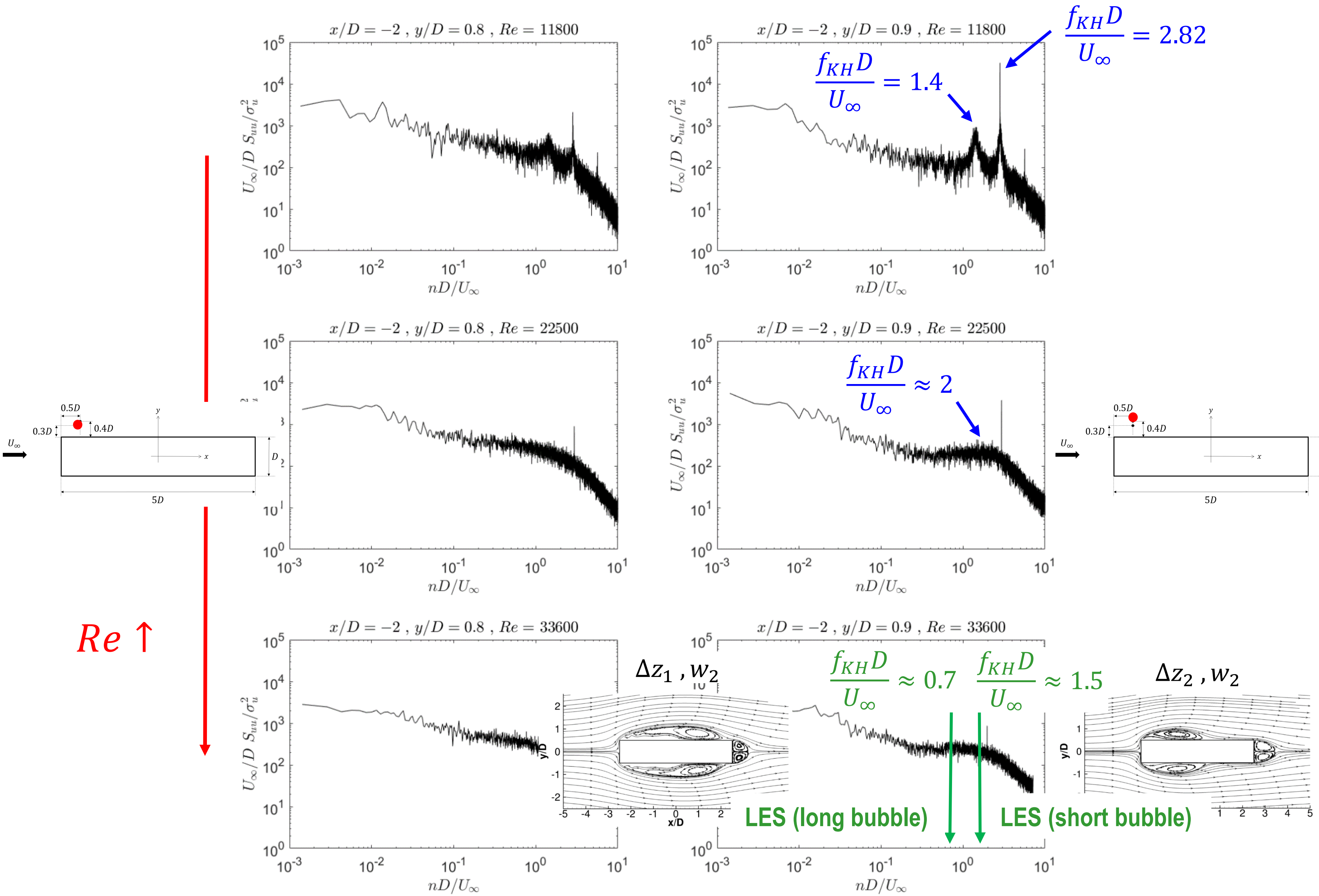
Reduced frequency of Kelvin-Helmholtz vortices

$$\frac{f_{KH} D}{U_\infty} \approx 1.5$$

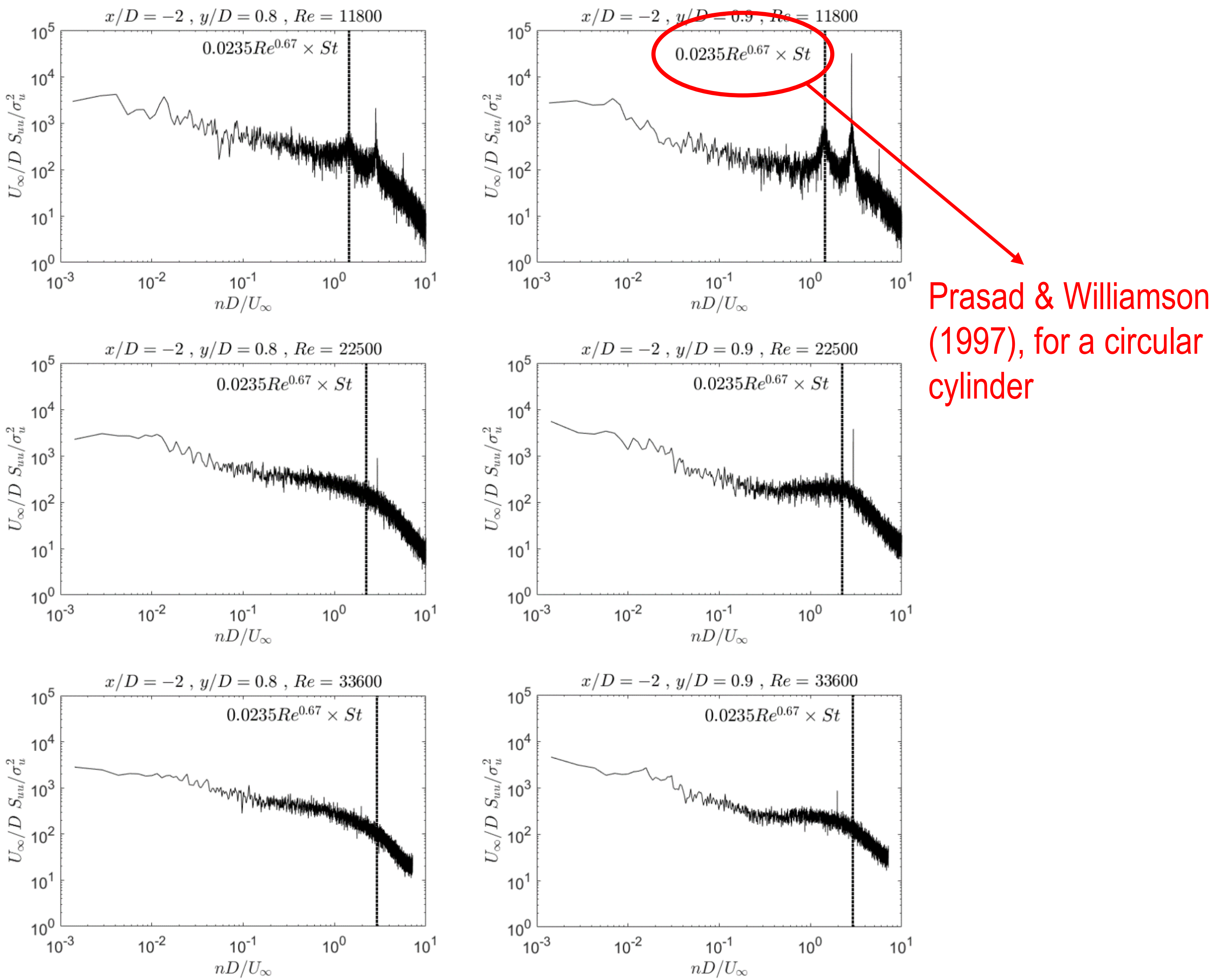




KELVIN-HELMHOLTZ FREQUENCY IN THE EXPERIMENTS



KELVIN-HELMHOLTZ FREQUENCY IN THE EXPERIMENTS

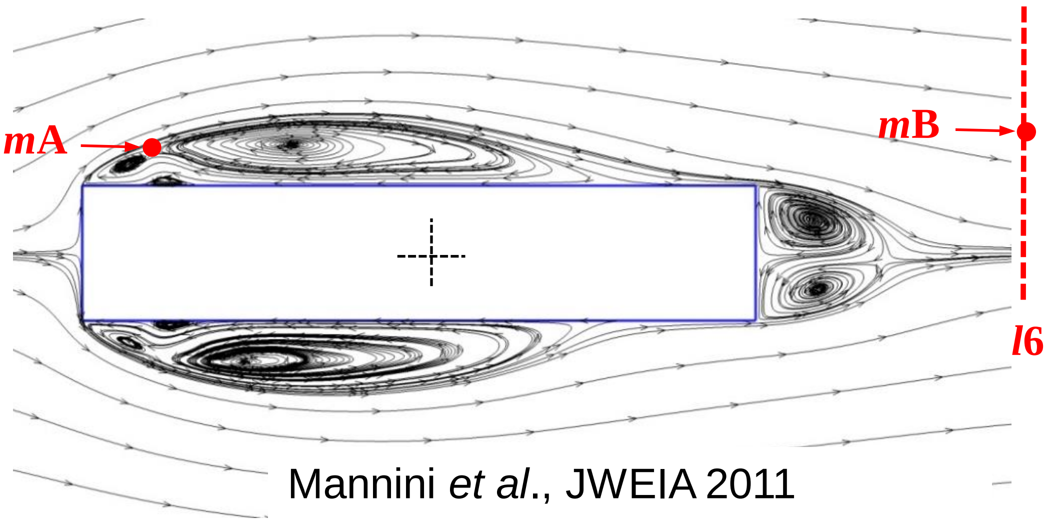


CONCLUSIONS AND PROSPECTS

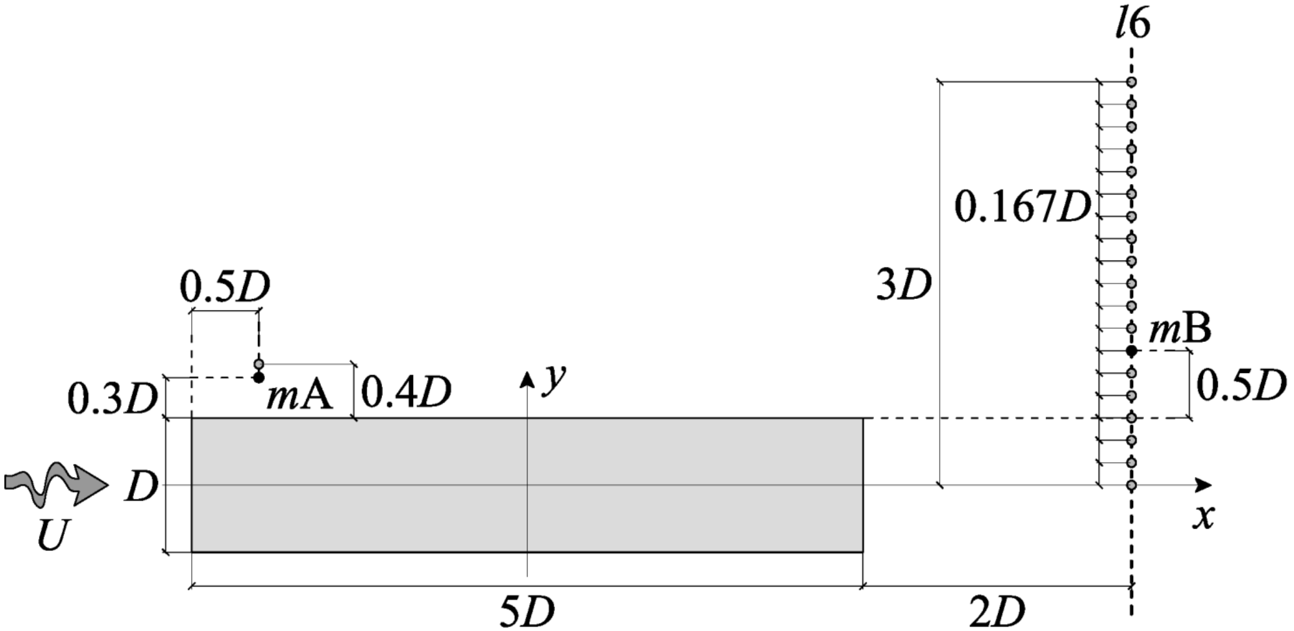
The mismatch between numerical and experimental results for the rectangular 5:1 cylinder was reconsidered through a close inspection of the dynamics of the shear layers.

- No clear correlation between the length of mean recirculation bubbles and first and second statistical moments of velocity fluctuations at the considered location in the shear layer.
- Correlation between the length of the mean recirculation bubbles, the Strouhal number and the location where the Kelvin-Helmholtz shear-layer instability occurs.
- The Kelvin-Helmholtz frequency in the LES simulations seems to be in better agreement with the experiments in the case of short recirculation bubbles.
- Experiments revealed apparent Reynolds number effects in the Kelvin-Helmholtz instability.
- No conclusive answer about the mismatch between LES and wind tunnel results
  → Further parallel experimental and numerical investigations are planned.

WAKE MEASUREMENTS

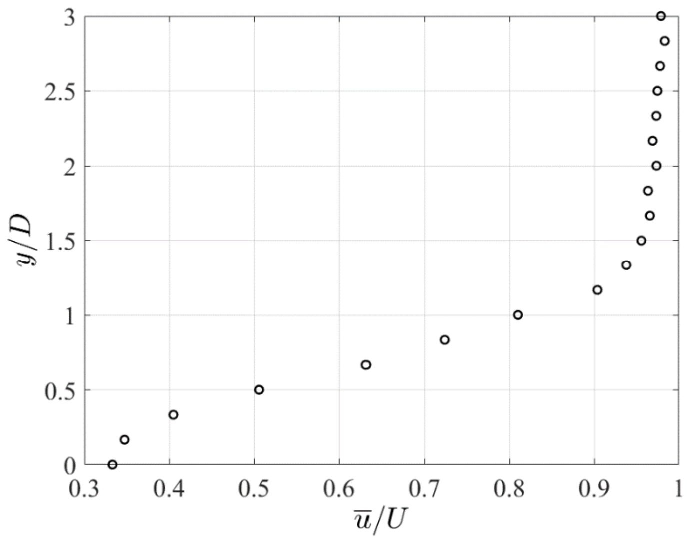


Mannini *et al*., JWEIA 2011

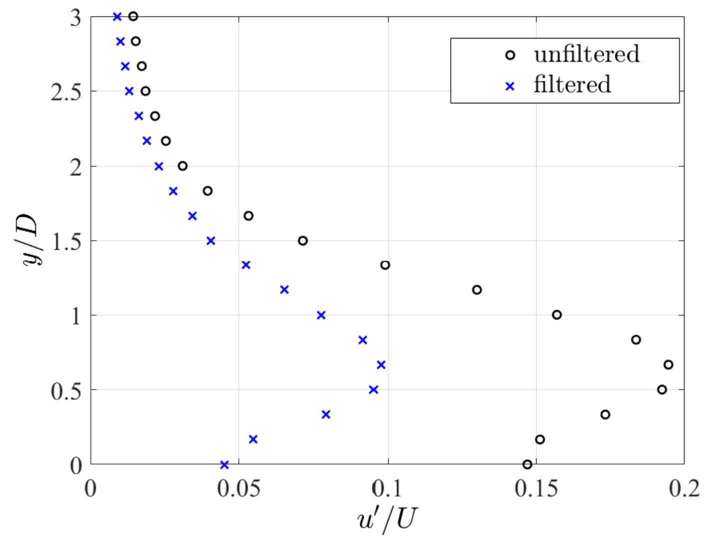


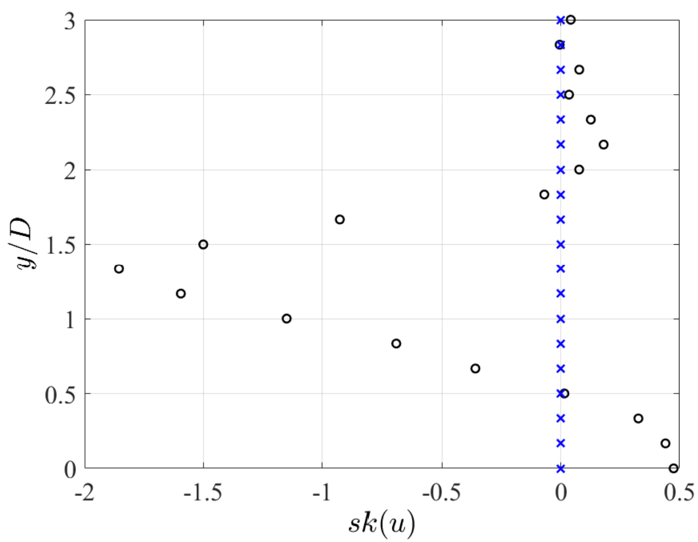
WAKE MEASUREMENTS

Streamwise mean velocity

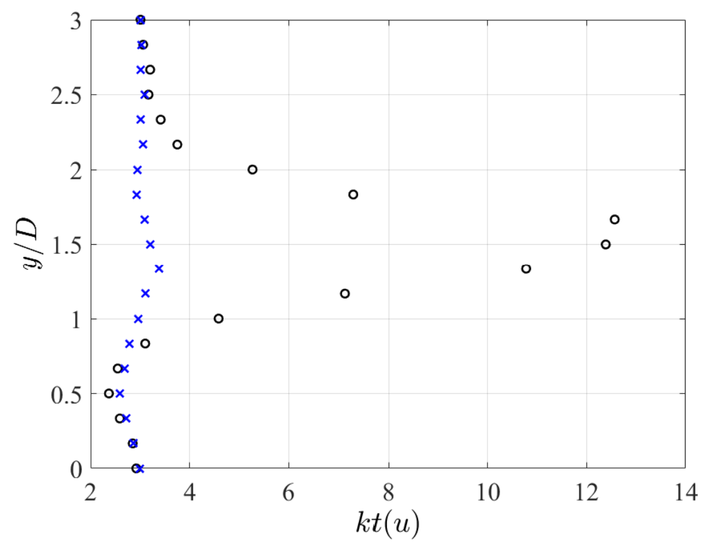


RMS of streamwise velocity





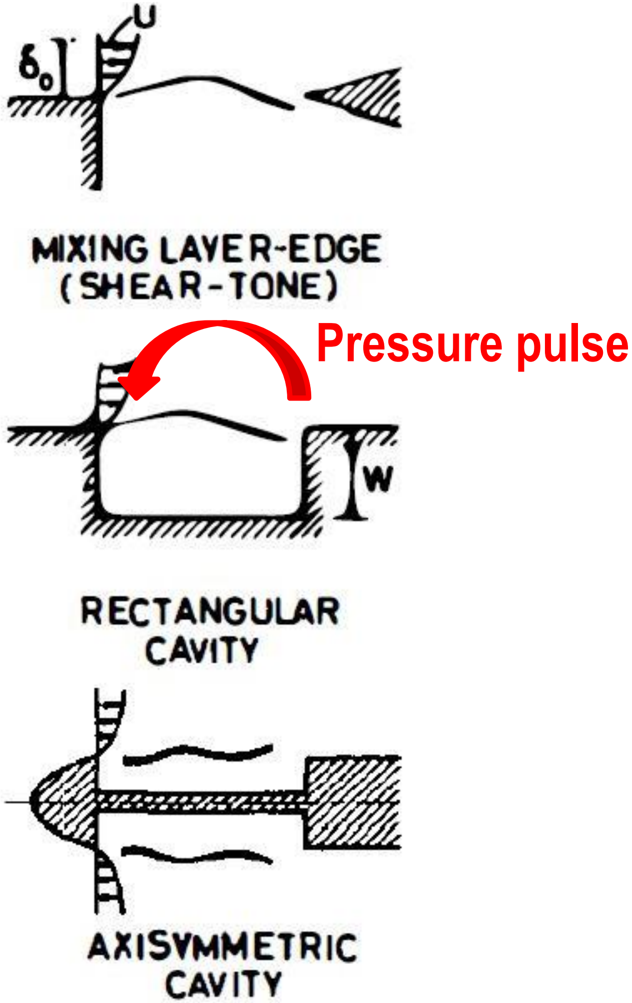
skewness

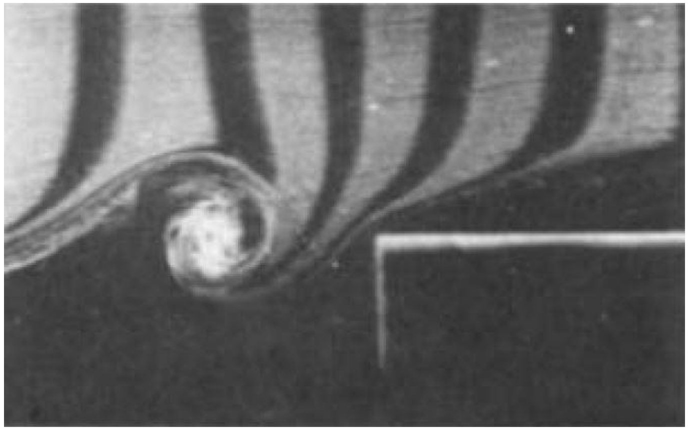


kurtosis

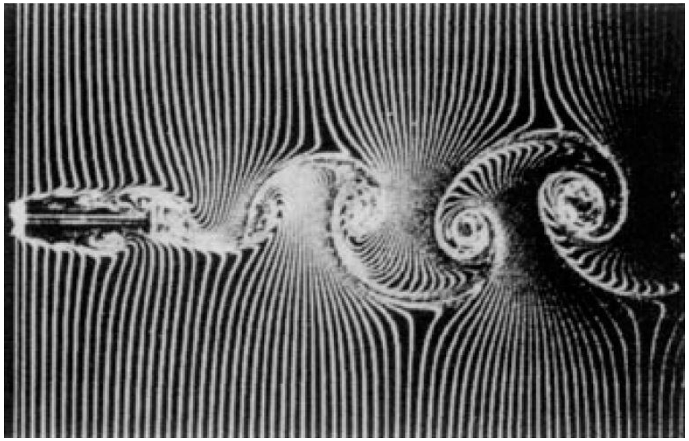
IMPINGING SHEAR-LAYER INSTABILITY

[from Rockwell & Naudascher, *Annu. Rev. Fluid Mech*. 1979]

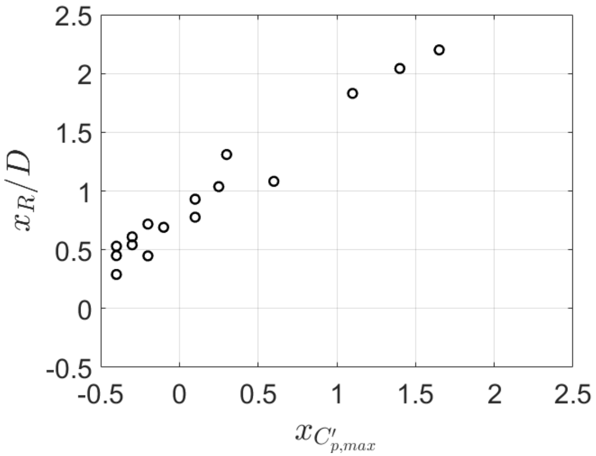


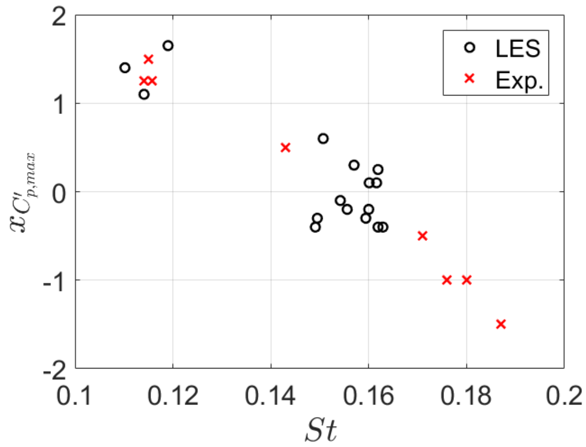


[from Nakamura *et al*., *J. Fluid Mech*. 1991]

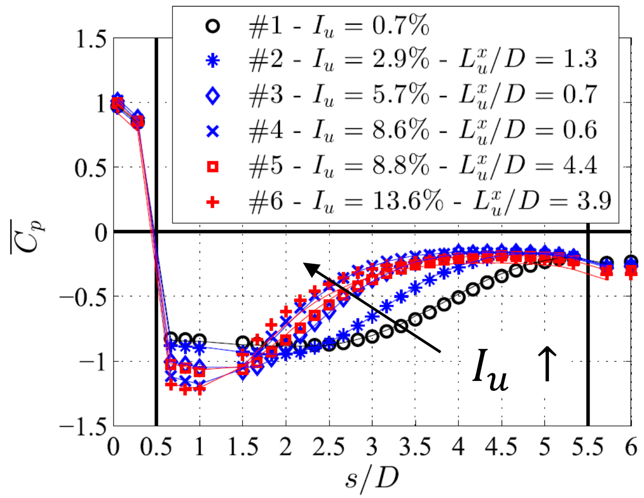


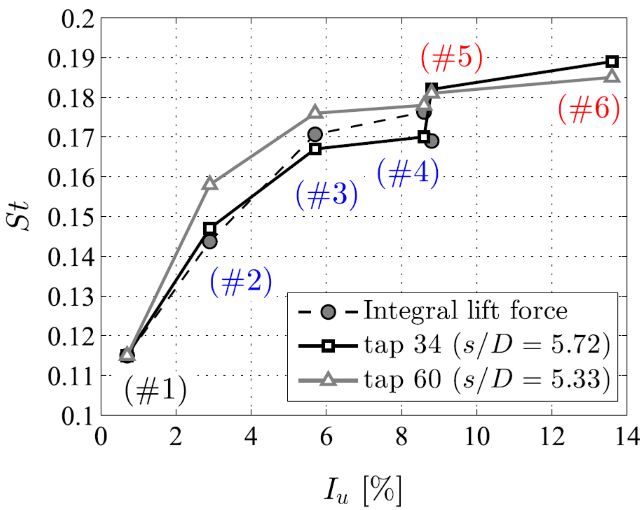
NUMERICAL vs. EXPERIMENTAL RESULTS



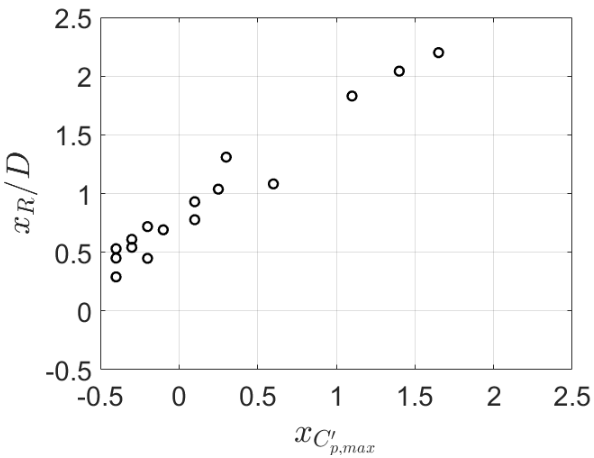


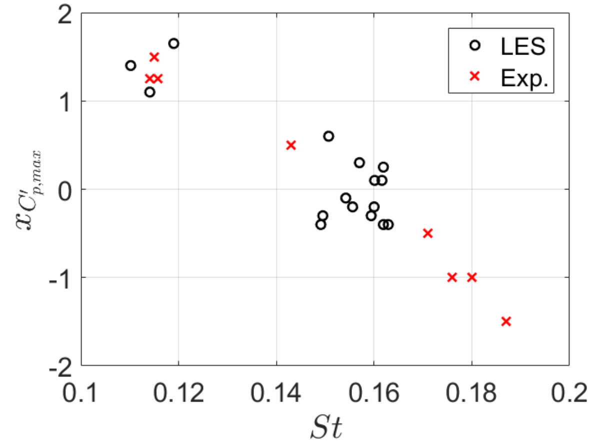
Experimental data in smooth and turbulent flow



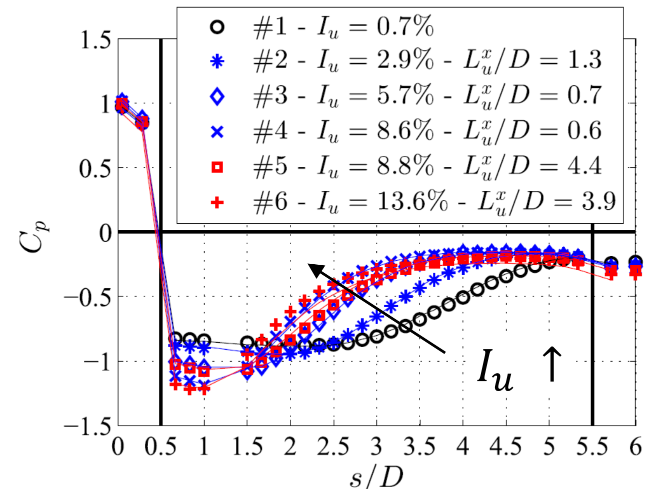


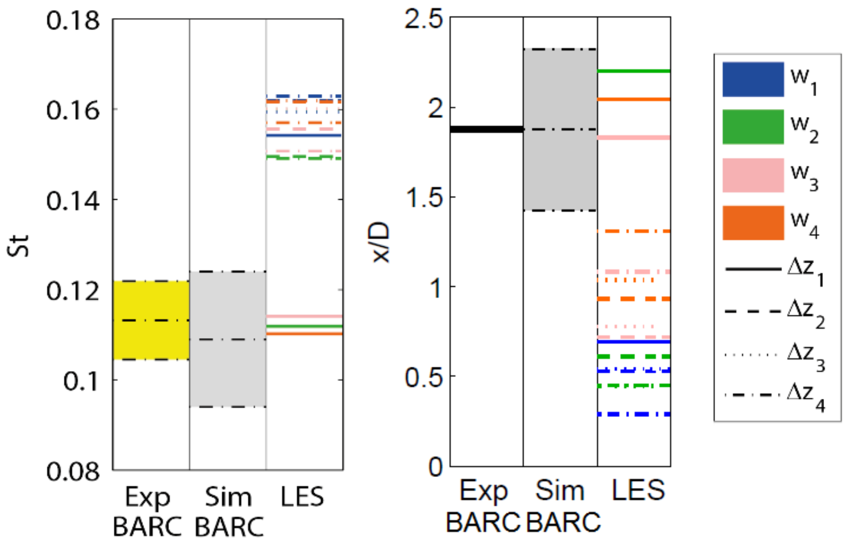
NUMERICAL vs. EXPERIMENTAL RESULTS

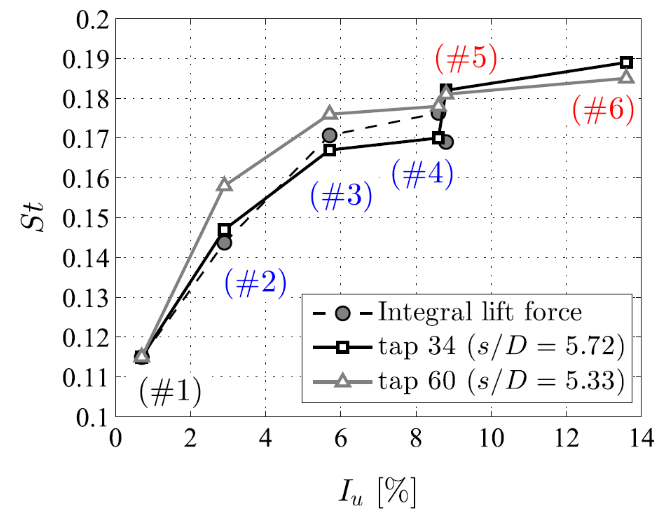




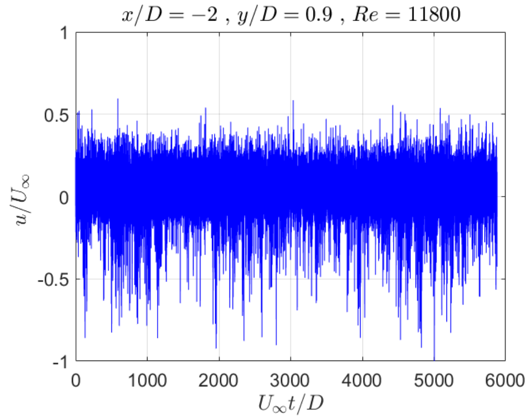
Experimental data in smooth and turbulent flow

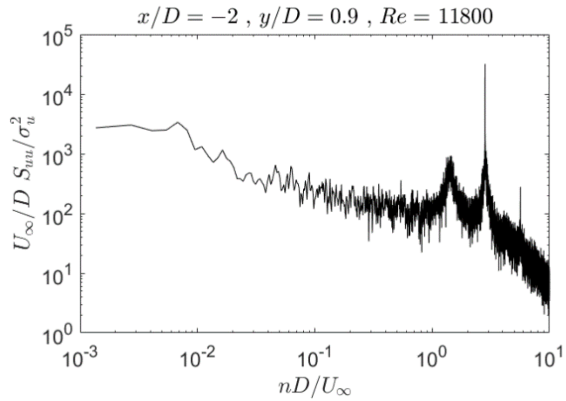


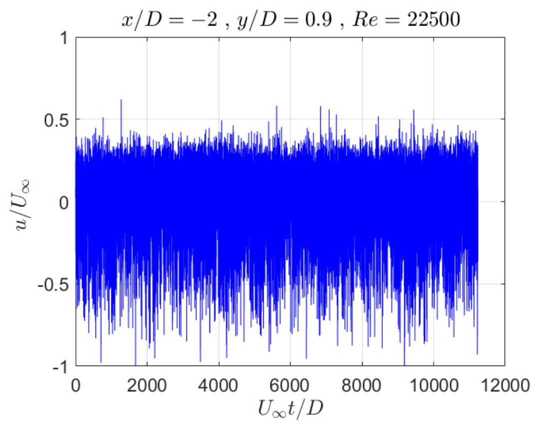


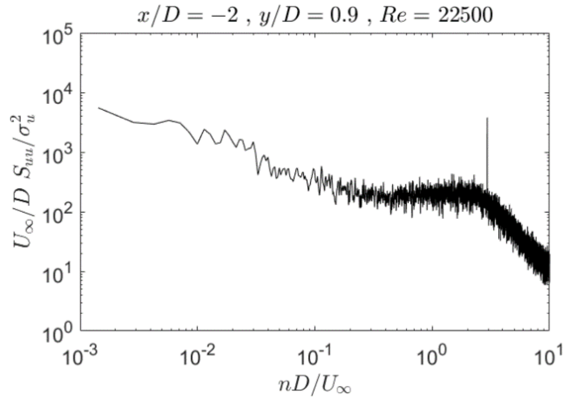


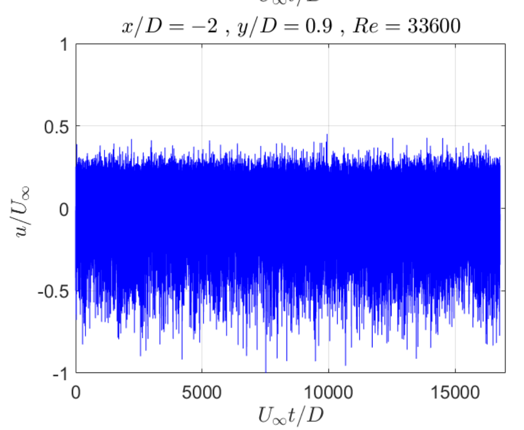
KELVIN-HELMHOLTZ INSTABILITY IN THE EXPERIMENTS

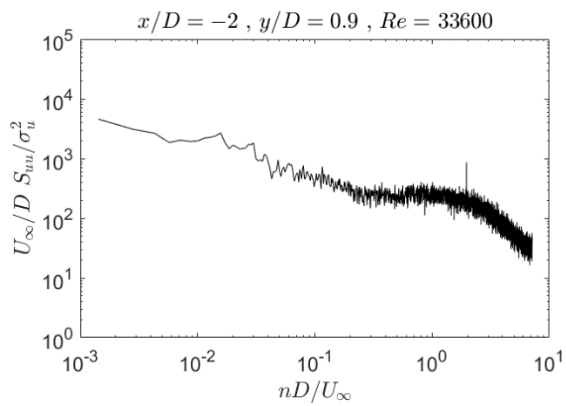












KELVIN-HELMHOLTZ INSTABILITY IN THE EXPERIMENTS